# NEHRP FINAL TECHNICAL REPORT

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# Quaternary geologic slip rates along the Agua Blanca fault: implications for hazard to southern California and northern Baja California

## Abstract

The Agua Blanca and San Miguel-Vallecitos Faults transfer ~14% of San Andreas-related Pacific-North American dextral plate motion across the Peninsular Ranges of Baja California. The Late Quaternary slip histories for the these faults are integral to mapping how strain is transferred by the southern San Andreas fault system from the Gulf of California to the western edge of the plate boundary, but have remained inadequately constrained. We present the first quantitative geologic slip rates for the Agua Blanca Fault, which of the two fault is characterized by the most prominent tectonic geomorphologic evidence of significant Late Quaternary dextral slip. Four slip rates from three sites measured using new airborne lidar and both cosmogenic $^{10}$Be exposure and optically stimulated luminescence geochronology suggest a steady along-strike rate of ~3 mm/a over 4 time frames. Specifically, the most probable Late Quaternary slip rates for the Agua Blanca Fault are 2.8 +0.8/-0.6 mm/a since ~65.1 ka, 3.0 +1.4/-0.8 mm/a since ~21.8 ka, 3.4 +0.8/-0.6 mm/a since ~11.8 ka, and 3.0 +3.0/-1.5 mm/a since ~1.6 ka, with all uncertainties reported at 95% confidence. These rates suggest that the Agua Blanca Fault accommodates at least half of plate boundary slip across northern Baja California. These rates are also applicable to the offshore Coronado Bank Fault.

## 1. Introduction

Geologic fault displacement histories are critical for tracking deformation and understanding seismic hazard in complex, multi-fault shear zones such as the southern San Andreas Fault (SAF) in California and Baja California, Mexico. South of the Big Bend in the SAF, ~50 mm/yr of slip is accommodated by multiple parallel and overlapping active faults that accommodate Pacific-North American plate boundary deformation both on-land and offshore (DeMets et al., 1990; 1994; DeMets, 1995; Bennett et al., 1996; Plattner et al., 200). Roughly 14% of total dextral plate boundary slip is transferred across the Peninsular Ranges of northern Baja California by the Agua Blanca Fault (ABF) and the San Miguel-Vallecitos Fault (SMVF) (Bennett et al., 1996; Dixon, 2002) (Figure 1). Both faults play in important role in accommodating slip between the Gulf of California rift zone and active SAF system faults near

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the western edge of the plate boundary. West-northwest directed slip accommodated by the ABF is fed into the offshore Coronado Bank Fault (Legg, 1991; Legg et al., 2007; Schug, 1987; Rockwell et al., 1993) and slip along the San Miguel-Vallecitos Fault system appears to transfer to the Rose Canyon Fault Zone (Grant and Rockwell, 2002; Dixon et al., 2000). Tectonic geomorphology, paleoseismology (Hatch, 1987; Schug, 1987; Hilinski, 1988; Hirabayashi et al., 1996), contemporary GPS (Bennett et al., 1996; Dixon, 2002), and in the case of the SMVF, abundant seismicity (Frez et al., 2000) and a 1956 M6.8 surface rupturing earthquake (Doser, 1992; Shor and Roberts, 1958), indicate that both structures are presently active and have been over the Late Quaternary. However, although together these faults accommodate nearly as much slip as the San Jacinto Fault (Blisniuk, Oskin, et al., 2013; rockwell et al., 1990) and more slip than either the Elsinore (Rockwell et al., 2018; Fletcher et al., 2011) or the Banning-San Andreas Faults (Gold et al., 2015), neither is typically considered in system-wide fault models or regional hazard estimates (Plesch et al., 2007; Field et al., 2015) because their geologic slip histories remain insufficiently constrained to confidently estimate the proportion of total slip accommodated by each fault.

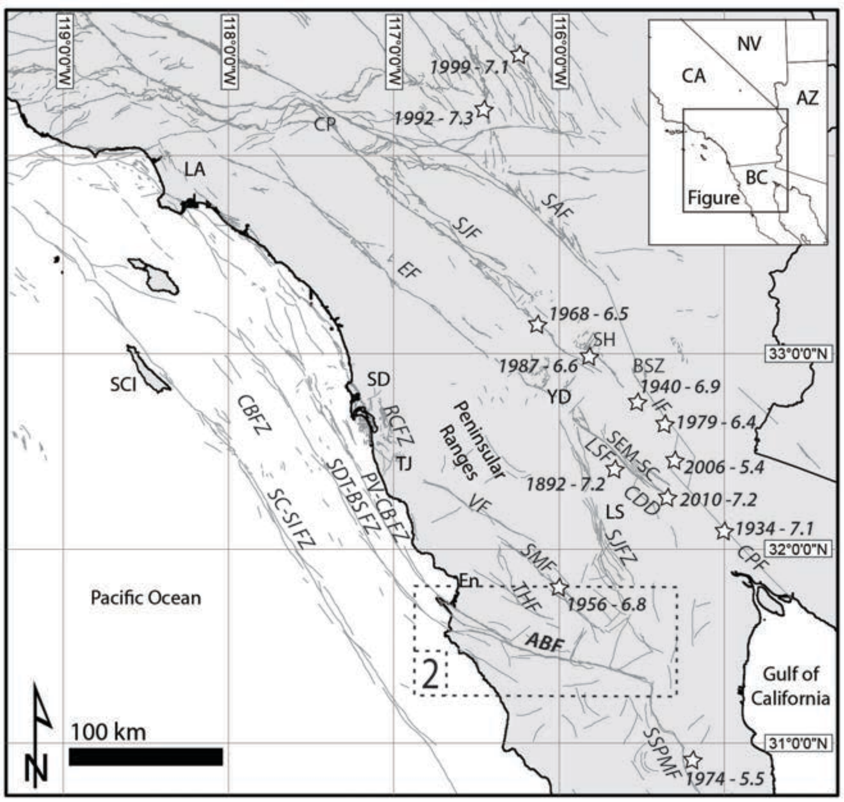


**Figure 1.** Fault map of the Southern San Andreas Fault system showing major regional earthquakes and faults in southern California and northern Baja California. Fault abbreviations: ABF: Agua Blanca Fault; BSZ: Brawley Seismic Zone; CDD: Canada David Detachment; CBFZ: Continental Borderland Fault Zone; CPF: Cerro Prieto Fault; EF: Elsinore Fault; LSF: Laguna Salada Fault; IF: Imperial Fault; PV-CB FZ: Palos Verdes-Coronado Bank Fault Zone; RCFZ: Rose Canyon Fault Zone; SAF: San Andreas Fault; SC-SI FZ: San Clemente-San Isidro Fault Zone; SDT-BS FZ: San Diego Trough-Bahia Soledad Fault Zone; SJF: San Jacinto Fault; SH: Superstition Hills; SJFZ: Sierra Juarez Fault Zone; SSPMF: Sierra San Pedro Martir Fault; SMF: San Miguel Fault; VF: Vallecitos Fault. Location abbreviations: SCI: San Clemente Island; CP: Cajon Pass; En: Ensenada; LA: Los Angeles; LS: Laguna Salada; SD: San Diego; TJ: Tijuana; YD: Yuha Desert.

The goal of this project was to acquire the first quantitatively constrained Late Quaternary slip rates for the Agua Blanca Fault. We used recently collected high resolution LiDAR data, geomorphic analysis, field mapping, and quaternary geochronology to identify and interpret 3 new slip rates sites along this fault system. Four slip rate measurements from the 3 sites show that since ~65 ka, the slip rate has remained relatively constant at ~3 mm/a, and we find no evidence of along-strike variability. These new measurements provide fresh insights into strain partitioning across northern Baja California and along the Continental Borderland. Below we summarize the conclusions from each site and discuss the implications for regional seismic hazard.

## 2. New Slip Rate Sites

We used newly acquired airborne lidar topographic data to search for geomorphic features preserving right-lateral slip along the Punta Banda, Santo Tomas, and Valle Agua Blanca sections of the western Aqua Blanca Fault (Figure 3). Three promising sites located along the western Punta Banda and central Valle Agua Blanca sections of the ABF record ~5, ~35, ~65 and ~180 m of right lateral slip (Figure 2). We mapped the broad-scale geomorphology at these sites remotely using the lidar and verified our observations and measurements in the field. Remote exploration, mapping and offset measurements were made using GIS or using LidarViewer (Kreylos et al., 2013). 10Be cosmogenic dating and optically stimulated luminescence dating were used to quantify the ages of geomorphic features at all three sites.

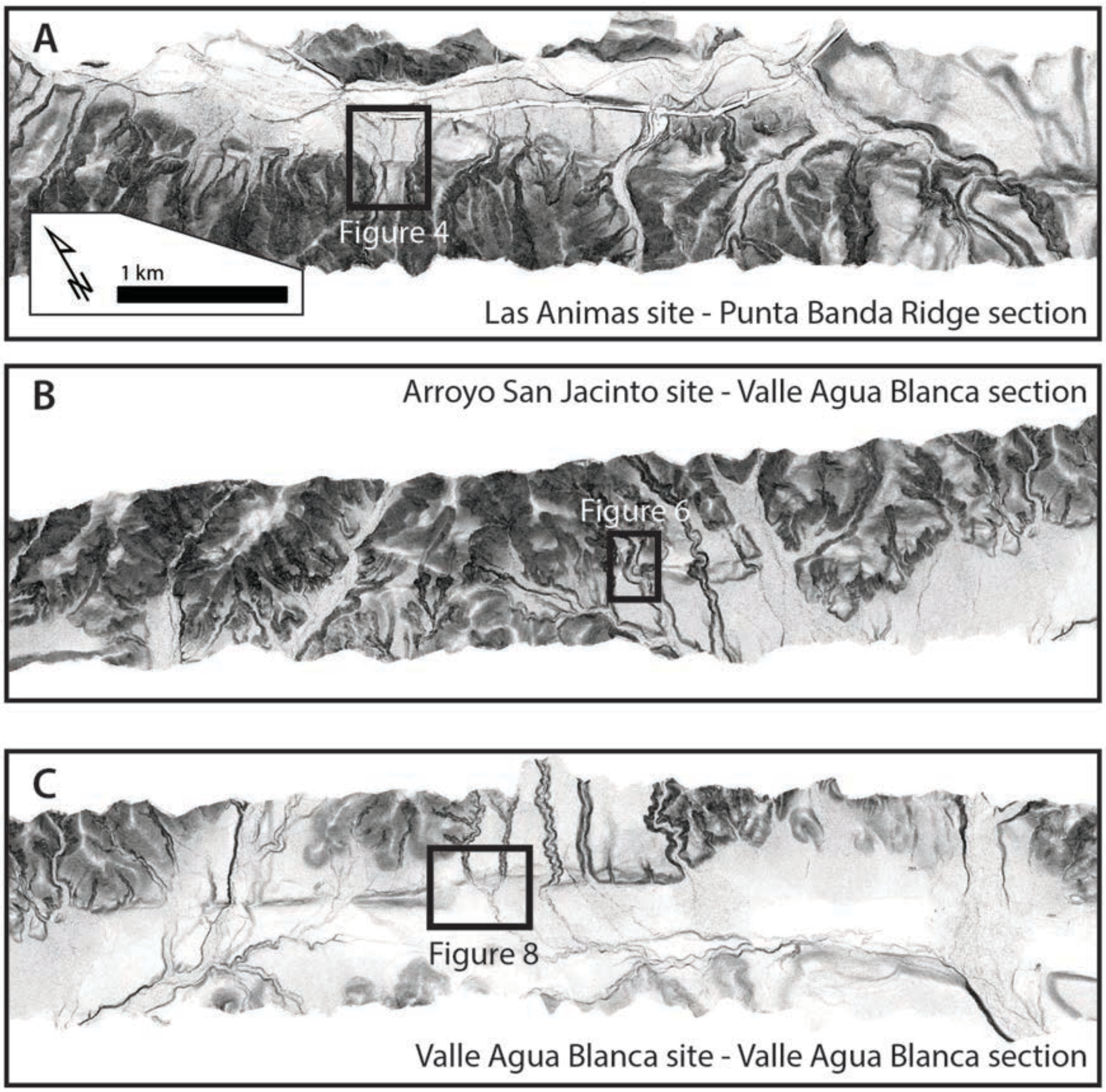


**Figure 2.** Slope-shaded strip maps from 0.5 m pixel resolution airborne lidar showing portions of the Agua Blanca Fault along which the new slip rates were

## *2.1 Site 1: Las Animas (31.639765°, -116.518718°)*

At the Las Animas site, the 300°-striking ABF coincides with the range front, separating Allisitos Formation to the south from Quaternary alluvial deposits across the fault (Fig. 3). Slip is primarily right lateral, with minor down-to-north dip slip. The conical form of a large alluvial fan (F1) north of the fault can be discerned from the topographic contours. West of the axis, the shoulder of F1 has been incised by two wide, low-relief channels, c1 and c2. Channels c1 and c2 record a post-aggradation history of incision and channel abandonment as the F1 alluvial fan was translated east along the ABF. F1 was likely constructed from sediments contributed almost entirely by the ~2 km$^2$ catchment upstream of the field area. Channel c1 incised into F1 first and was then abandoned as lateral fault slip translated the lower elevation trailing edge of F1 to a position at the catchment mouth. Realigning the F1 axis predicts ~180 m of offset when restored to the center of the catchment (Fig. 3). Three of four dates from F1 clustered tightly between 64.2 and 66.2 ka (Fig. 5). The younger date (52.2 ka) does not overlap the others within 2σ internal errors, and is morphologically different, so was excluded. The age and offset of F1 suggest a slip rate of ~2.7 mm/yr. A shorter timescale slip rate was also determined from Channel C1. Our interpretation is that following ~115 m of F1 displacement (or 180 m total slip), c1 was incised by lateral erosion forming the F1-c1 riser and depositing the c1 bar at approximately 21.8. The F1-c1 terrace riser is offset by ~65 m, indicating a slip rate of ~3 mm/yr since 21.8 ka.

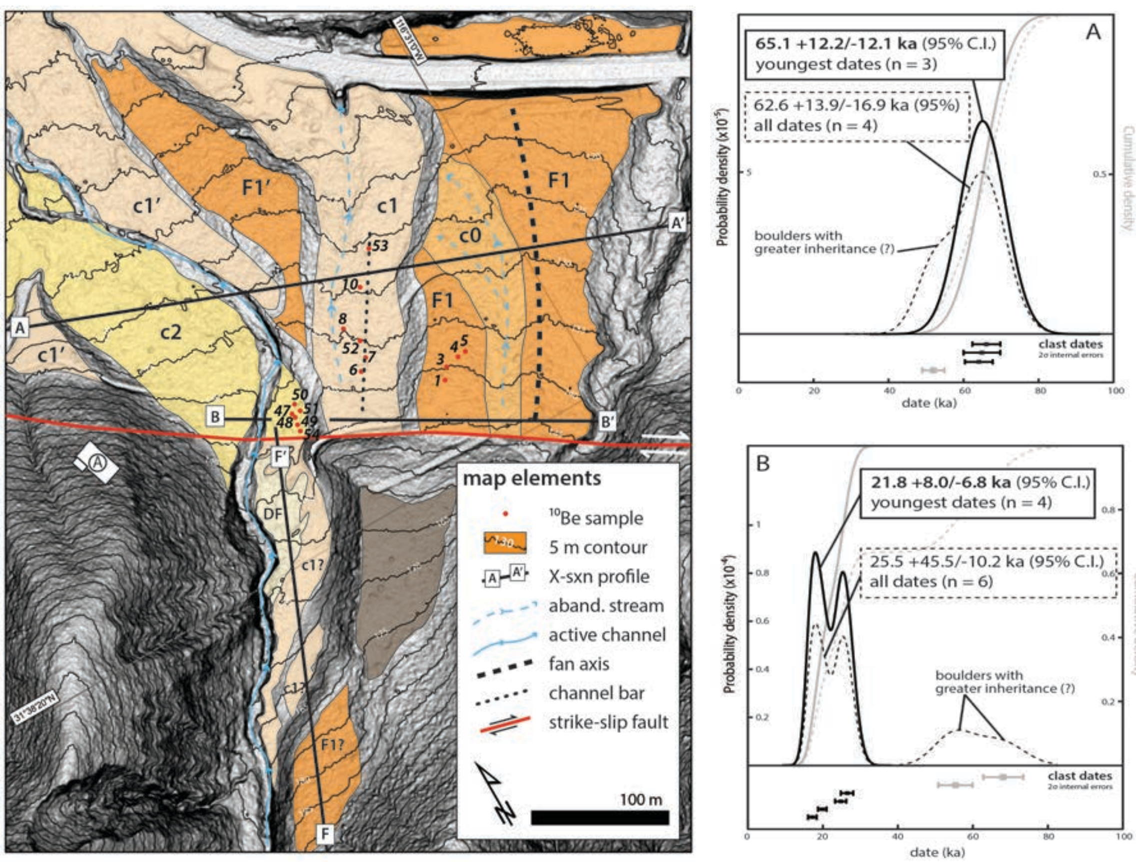


Figure 3. [Left] Geomorphic map of the Las Animas site. [Right] Cosmogenic $^{10}$Be result from boulders sampled on the F1 (a), c1 (b) surfaces at the Las Animas site.

## *2.2 Site 2: Arroyo San Jacinto Site (31.489113, -116.229269)*

At this site, located at the western end of Valle Agua Blanca, the 285°-striking Aqua Blanca Fault traverses the mouth of an alluvium-filled embayment at the convergence of 4 small (~0.4 -1 $km^2$) catchments that drain south into Arroyo San Jacinto. The fault displaces multiple alluvial surfaces (Fig. 4). The slip rate site lies within a channel dissecting Q5 that preserves ~25 and 40 m of lateral displacement at its east and west walls, respectively. The floor of this channel widens substantially downstream of the fault and is filled by a coarse clastic deposit (Q2) into which the modern channel thalweg has incised by up to ~2 m. Where the modern thalweg crosses the fault it diverges from a single channel downstream into two roughly parallel branches: a less incised channel that continues upstream straight across the fault, and the presently active channel, which bends right and parallels the fault for ~5 m before continuing upstream. When projected to the fault, separations between the thalweg and east wall of the channel incising Q2 record 5 ± 1 m of eastward deflection. We interpret this deflection to be the result of post-incision tectonic offset. The median date of Q2 from cosmogenic 10Be was interpreted to be 1.6 +1.4/-0.8 ka, and provides a maximum timing for incision. We interpret the western Valle Agua Blanca section of the Agua Blanca Fault slip rate to be ~3.0 +3.0/-1.5 mm/a.

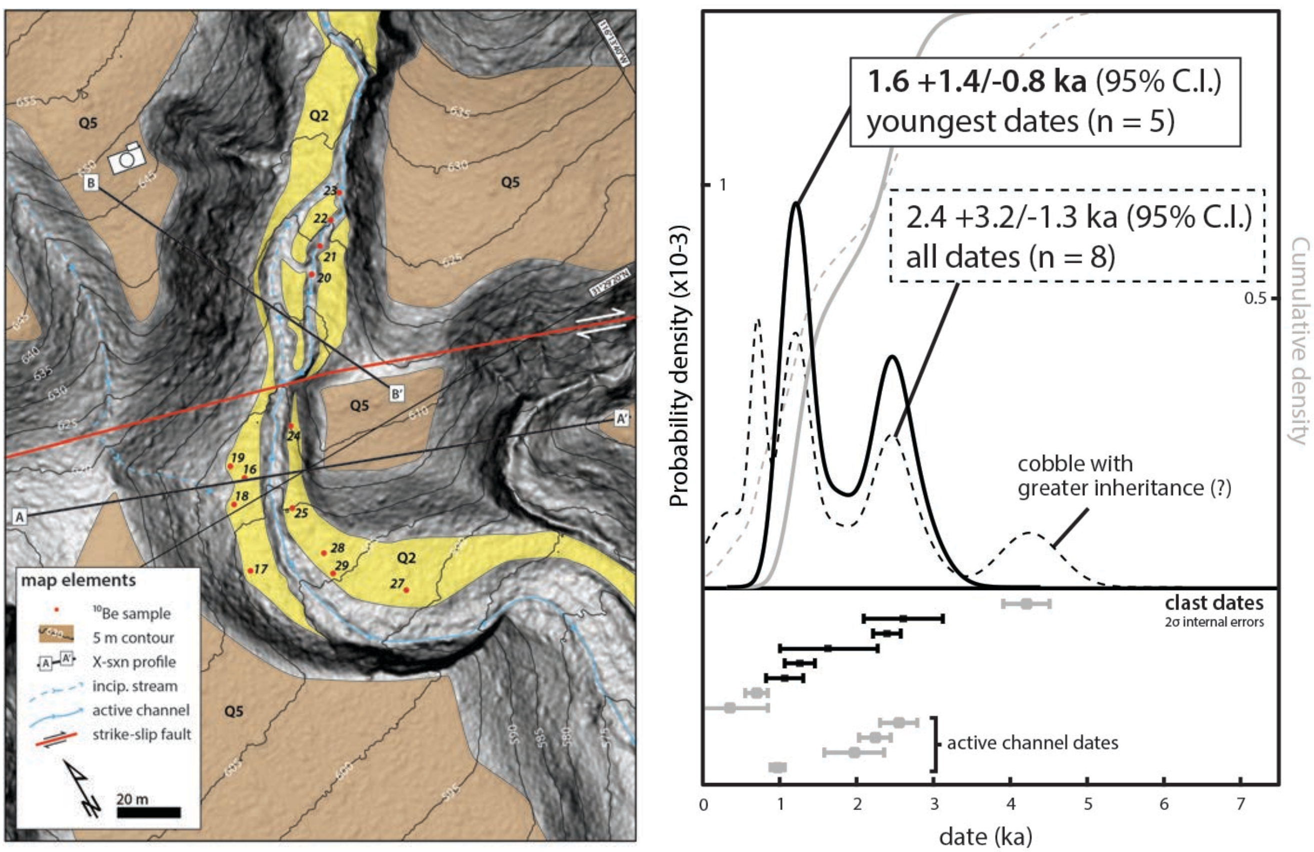


**Figure 4.** [Left] Geomorphic map of the Arroyo San Jacinto site. [Right] Cosmogenic $^{10}$Be result from cobbles sampled on the Q2 surface at the Arroyo San Jacinto site.

## *2.3 Site 3: Valle Agua Blanca Site (31.476904, -116. 181411)*

At this site in the central Valle Agua Blanca, the 290°-striking ABF makes an ~350 m right step to bound the northern side of the valley, where it truncates the toe of an extensive alluvial fan complex (Fig. 6). At this site, the radial form of a nearly symmetrical alluvial fan (Qaf) can be recognized with the lidar. The axis of the fan appears to curve slightly to the SSW, and the fan axis calculation procedure of Gold et al. (2015) suggests an average orientation of 15-20°. Realigning the fan axis with the east and west margins of its interpreted source channel results in 35-45 m of slip since the deposition of Qaf (Fig. 5). Three OSL dates from sandy lenses in the head of the Qaf fan at the Valle Agua Blanca site that are exposed in paleoseismic trenches across this section of the fault give weighted mean dates of 10.8, 12.1, and 12.4 ka with standard errors of ±6%. This leads to an estimated slip rate of 3.4 +0.8/-0.6 mm/a.

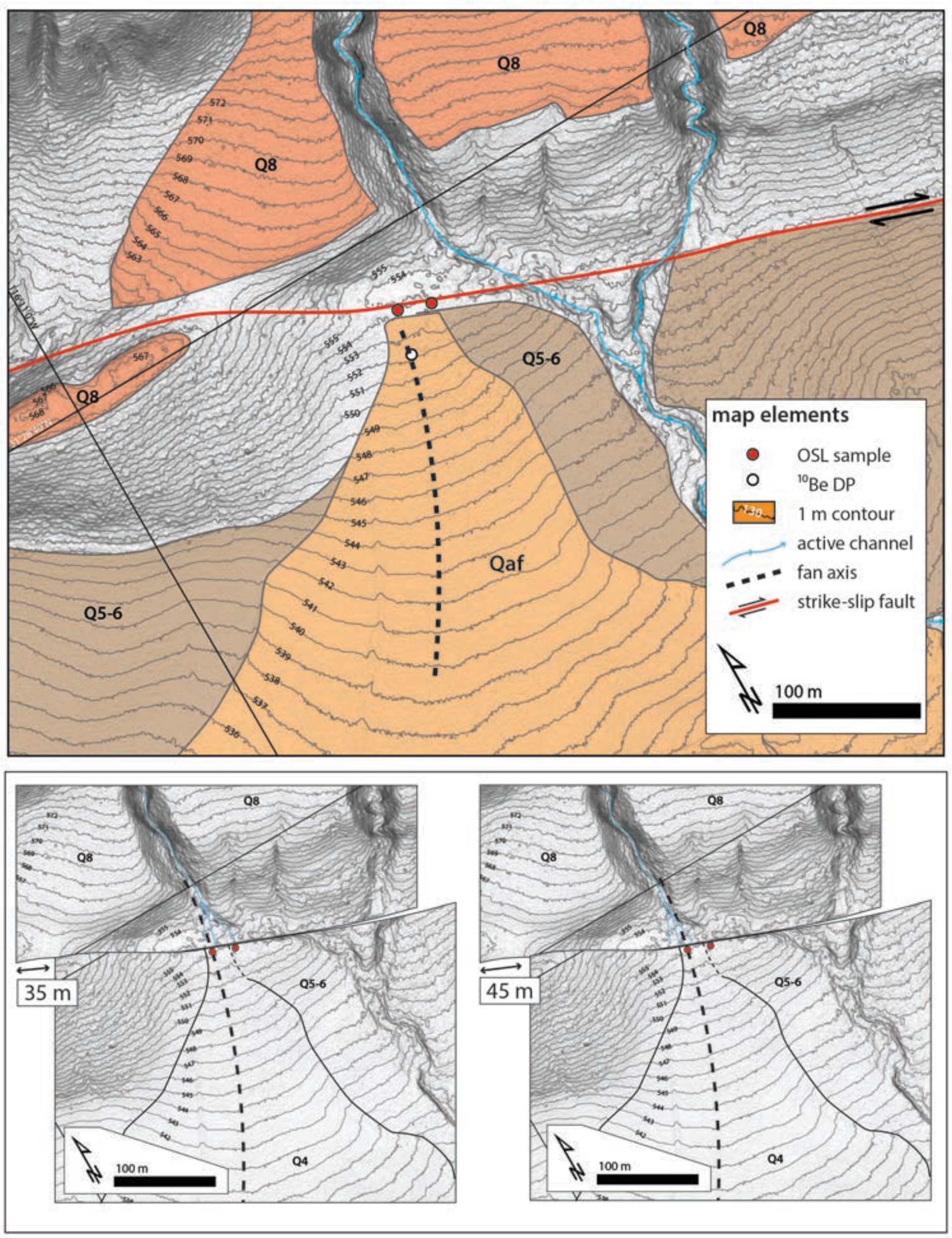


**Figure 5.** [Top] Geomorphic map of the Valle Agua Blanca site. [Bottom] Offset reconstructions of the Qaf alluvial fan.

# 3. Implications

## *3.1 Comparison to prior geologic slip rate estimates*

The most probable slip rates for the western half of the ABF over 65.1 ka, 21.8 ka, 11.8 ka and 1.6 ka time frames vary little from each within error, suggesting that the Late Quaternary slip rate has remained essentially constant over time and along strike (Fig. 6). These new rates overlap previous geologic estimates within error (Hatch, 1987; Schug, 1987), but are somewhat lower than the 4-6 mm/a rates often quoted from these studies. A feature of the previous measurements that our rates do not support is a westward decrease in the slip rate, which has previously been interpreted as an indication of slip transfer to the Maximinos Fault, which parallels the ABF on the southern side of Punta Banda Ridge.

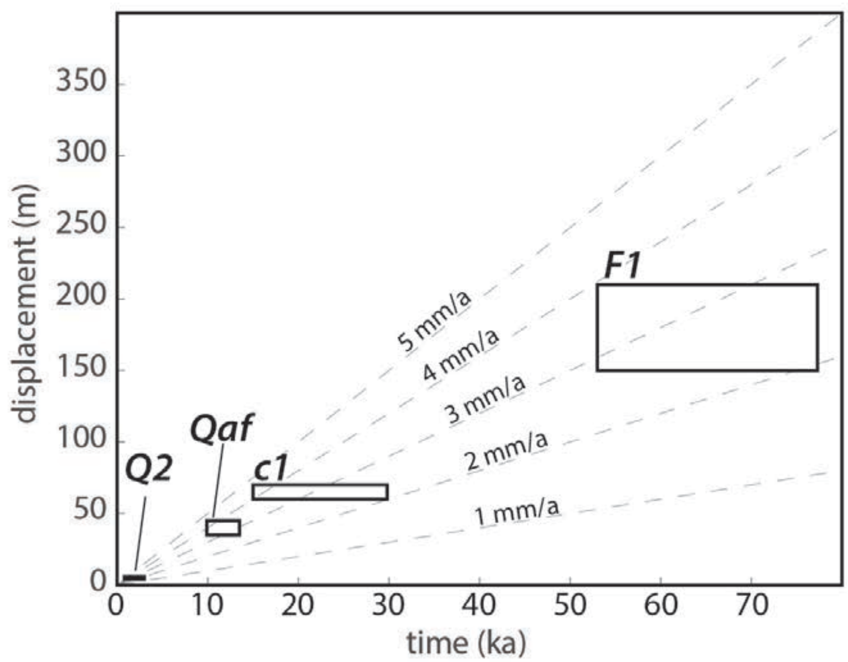


**Figure 6.** Displacement-time plot for the four new slip rates

## *3.2 Comparison to GPS rates*

The earliest estimates of strain accommodation across northern Baja California suggested that roughly 14% or ~7 mm/a of slip is split between the Agua Blanca and San Miguel-Vallecitos Faults (Bennett et al., 1996). The preferred solution in this study placed 4 ± 2 mm/a of slip on the ABF, all of which was modeled as transferring to the San Clemente fault offshore, and 3 ± 3 mm/a on the SMVF. Dixon et al. (2002) measured 4-8 mm/a of slip across both systems, but how the slip was partitioned between the faults depends on the crustal model. Using an elastic half-space rheology placed 2.2-3.1 mm/a on the ABF and 2.4-3.7 mm/a on the SMVF. Incorporating a the effects of a viscoelastic lower crust/upper mantle using a coupling model suggests instead 6.2 ± 1.0 mm/a on the ABF and 1.2 ± 0.6 mm/a accommodated by the SMVF, more compatible with the earlier geologic estimates. The new geologic rates are more consistent with GPS solutions that place approximately equal slip on the ABF and SMVF.

## *3.3 Off-shore slip*

The primary fault systems west of the Pacific coast transfer slightly compressive right lateral slip north along the Continental Borderlands (Fig. 1). From west to east the are the San Clemente-San Isidro, San Diego Trough-Bahia Soledad, and Palos Verdes-Coronado Bank Fault.

The horizontal GPS rate across all three systems is 5.9 ± 1.8 mm/a (Larson, 1993), 4 ± 2 or 3 ± 2 mm/a of which may be concentrated on the San Clemente Fault (Bennett et al., 1996; Dixon, 2002). This rate for the San Clemente Fault also matches GPS residuals of 4.3 ± 0.8 mm/a between the Pacific Plate and Baja California (Plattner et al., 2007). Ryan et al. (2012) measured a submarine geologic slip rate of 1.5 ± 0.3 mm/a over the past 12,270 yr along the San Diego Trough Fault. The San Clemente Fault is mapped as extending past the intersection of the ABF, while the San Diego Trough fault is usually mapped as coming on shore south of Punta Banda Ridge (Legg, 1991; Legg et al., 1987; 2007). Rockwell et al. (1989) measured right lateral slip rate of 1 ± 0.6 mm/a along the Maximinos fault, which goes offshore south of Punta Banda Ridge, but north of the mapped trance of the Bahia Soledad fault. Whether this slip is taken up by the San Diego Trough-Bahia Soledad system or the ABF-Coronado Bank system is unclear. Regardless, the new 3.0 +1.4/-0.8 mm/a (65 ka) and 2.8 +0.8/-0.6 mm/a (22 ka) slip rates from the Las Animas site (closest to the offshore system) are compatible within errors with the total 5.9 ± 1.8 mm/a rate (Larson, 1993) when summed with the Maximinos (Rockwell et al., 1989) and San Diego Trough (Ryan et al., 2012) geologic rates and the San Clemente fault GPS rate. Much more slip on the Agua Blanca fault, and thus the Coronado Bank Fault, would require either a higher total rate or a ~zero rate on the San Clemente fault, which is inconsistent with seismic and bathymetric observations of its surface trace (Legg et al., 2007).

### *3.4 Seismic Hazard*

The new slip rates are relevant for at least the western half of the ABF, which comprises three of the five roughly 20-30 km segments that define the fault. Although the junctions between the faults are releasing, they do represent greater complexity where the fault changes either strike or dip, or both, and thus probably do nothing to facilitate coseismic rupture propagation. If between one and three segments link up during earthquakes to produce 20-60 km-long surface ruptures, moment magnitudes of between ~6.6 and 7.3 should be expected (Wells and Coppersmith, 1994). This suggests average displacements of ~75-150 cm, which if the new ~3 mm/a slip rates are correct, translates to roughly 2-4 earthquakes every thousand years, or recurrence between 250 and 500 years. Schug (1987) found plausible paleoseismic evidence for a rupture in the past 280 ± 90 years, which if correct suggests that the fault may be at or near the end of a seismic cycle.

## 4. Broader Impacts and Dissemination

This project supported salary and research costs for an early career faculty member (PI Behr) and a Ph.D. student (Peter Gold). Ph.D. student Gold is completing his dissertation in May, 2018, and this work will constitute a significant component of his dissertation. This work will be submitted for publication to GSA Bulletin or a similar journal in summer, 2018. The reference is:

Gold, P.O. , **Behr, W.M.**, Fletcher, J.M., and Rockwell, T.K., Late Quaternary slip history for the Agua Blanca Fault, northern Baja California Part 1: New geologic slip rates, *to be submitted to* GSA Bulletin.

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